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Individually controlled localized chilled beam in conjunction with chilled ceiling: Part 2 – Human response

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ABSTRACT
The response of 24 subjects to the local environment established by localized chilled beam combined with chilled ceiling (LCBCC) was studied and compared with response to the environment generated by mixing ventilation combined with chilled ceiling (CCMV) at two temperature conditions of 26°C and 28°C. The supply airflow rate from the LCBCC was controlled by the subjects within the range of 10 to 13 L/s. In the case of CCMV subjects did not have control over the flow rate. The results showed that occupants' overall and local thermal sensation acceptability improved at the workstation by using the LCBCC system compared to CCMV. The subjects felt less warm with the LCBCC and their thermal sensation was close to neutral. Most of the subjects achieved acceptable air movement at the workstation by the provided individual control of the flow rate from the LCBCC. Need for air movement was reported in the case of CCMV.

PRACTICAL IMPLICATIONS: From the energy saving prospective in commercial buildings, creating local environment where occupants spend most of their active time has little been studied. This study provides information for human response to generated indoor environment by localized chilled beam combined with chilled ceiling.

Keywords: Human response, Localized chilled beam, Chilled ceiling, Individual control, Local environment

Introduction

Nowadays, decreasing the energy consumption in buildings becomes important. It is documented that energy consumption in buildings is much more compared to the energy used for transportation and in industry (Pérez-Lombard et al., 2008). Therefore the effort to reduce the energy consumption in buildings is growing rapidly. Among various methods for cooling and heating the spaces, high-temperature water cooling and low-temperature water heating systems have become more popular (Costelloe and Finn, 2003; Virta et al., 2005). Chilled ceiling (CC) panels and chilled beam system are two cooling systems working on this principle. Chilled beam (CB) is one of the Water-Air systems widely used in offices and commercial buildings. Acceptable thermal comfort and air quality have been provided by employing this system (Riffat et al., 2004). The major benefit of using CC system is to take away the generated heat load out of the occupied zone and keep more homogeneous thermal environment between the occupied zone and the surroundings by means of radiation. Ventilation consumes substantial part of the energy used in buildings. The present total volume ventilation strategies are used, i.e. the entire room volume is ventilated. Reduction of the ventilation airflow rate will bring energy savings but is not recommended because it will have negative impact on the indoor air quality.

Non-uniform air distribution aiming at ventilating locally room zones where the occupants are present has potential to improve the local environment at reduced ventilation rate. In this way also energy can be saved. In this respect creating a local-climate in offices where occupants spent most of the time at the workstations is promising direction of development. The possibility to provide the occupant with control of the local environment will improve its quality. However at the same time the room environment apart of the workstation should be at least acceptable. Localized chilled beams have been developed to establish a local-climate around the seated person via individual control. However research shows that applying LCB alone could create good local environment at workstation but at the same time will reduce the acceptability of the remaining part of the occupied zone in rooms (Uth et al., 2014).

The performance of LCB combined with CC was studied with regard to the generated indoor condition. The present study present results on human response to the generated indoor environment.

METHOD

The study was conducted in two climate chambers. The main test chamber, 4.1 m (L) × 4.0 m (W) × 3.1 m (H) was decorated to simulate a realistic office environment with two workstations, **Error! Reference source not found.**. Heat from direct solar radiation on part of the floor near the windows was simulated by electric heating foils (2.0 m × 4.0 m). In addition, five radiant panels with total area of 6.24 m^2 were used to simulate solar radiation on the wall. About 75% of the ceiling was covered by 18 cooling panels. A neighboring climate chamber was set-up and used as an acclimatization place.

Two different systems, namely Localized Chilled Beam combined with Chilled Ceiling (LCBCC) and Chilled Ceiling combined with Mixing Ventilation (CCMV), were applied. An active chilled beam was modified by installing wings so that the supply air was directed to the occupant. The airflow rate could be controlled by the occupant to some extent by means of a desk-mounted knob. The mixing ventilation (MV) system was comprised of two ceiling-mounted linear diffusers. Fixed amount of air was supplied by the MV system throughout the experiment.

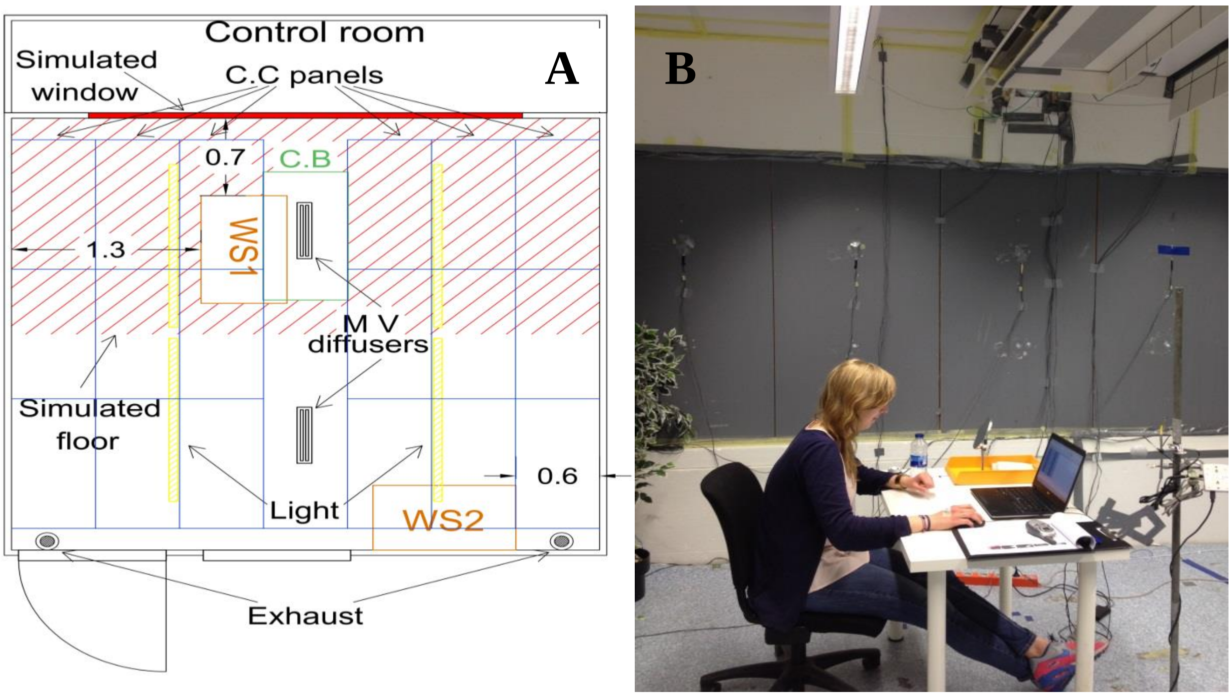

Figure 1. A)The room layout with tested systems, B) Position of the radiant window and the LCB to WS1

Twenty-four university students, 12 males and 12 females, participated in the experiment. The subjects were divided into 6 groups of 4 people. Each group participated in five experiments. They were asked to wear casual summer clothing in the introductory sessions.

The experimental conditions during the five experiments are listed in Table 1. The designed supply flow rate and room temperature were according to category II, EN 15251 (2007) for very low polluting building.

Table 1. Test conditions

Case	System	t (°C)	Supply airflow rate (L/s)
1	LCB+CC	26	10- 13 (individual control)
2	LCB+CC	28	10- 13 (individual control)
3	LCB+CC	28	10- 13 (individual control)
4	CC+MV	28	13 (no individual control)
5	CC+MV	26	13 (no individual control)

Each experiment took two hours, divided into 30 min acclimatization period and 90 min exposure period in the office room. Experiments in the simulated office comprised three sessions of 30 min at each WS. The first 30 min spent at WS1, followed by 30 min at WS2 and finally last 30 min again at WS1, Figure 2. Throughout the paper the response of the subject at the end of the first and second exposure period at WS1, i.e. before and after moving, is identified as WS1-1 and WS1-2, while with W2-1 at the end of the exposure period at WS2..

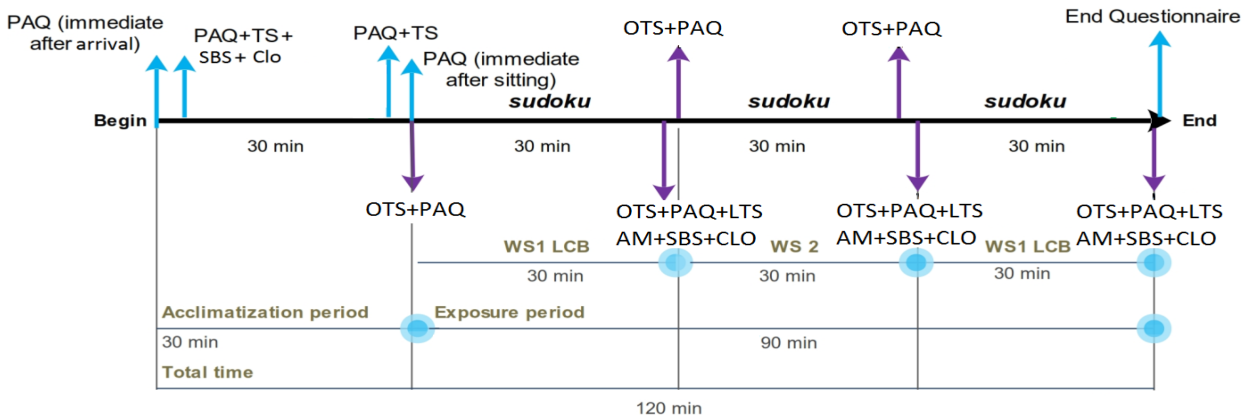

Figure 2. Experiment procedure

Overall body thermal sensation (OTS) and local thermal sensation (LTS) of body parts were evaluated by continuous seven point ASHRAE thermal sensation scale. Two-part continuous scale with end points coded as -1 (clearly unacceptable) and +1 (clearly acceptable) with an interval between -0.1 (just unacceptable) and +0.1 (just acceptable), was used to assess the acceptability of air movement (AM). The scales are recommended in EN15251 (2007). Questions on perception of air movement on each body part (Yes/No) and preference for more air movement (more, less or no change of air movement) were asked.

The normality distribution of data was subjected to Shapiro-Wilcoxon test with significance level of $p<0.05$. In the case of data not normally distributed, non-parametric tests were used to analyze the results. Since in the present study the same group of people was exposed to different thermal conditions generated by the applied systems, variables in the experiment have dependent relationship. Therefore, two groups of results were compared as dependent variables by using Wilcoxon matched pairs test, with the significance level of 0.05.

RESULTS

Overall and local thermal sensation

All values of OTS can be classified within the range of neutral and slightly warm, Figure 3. Thermal sensation in cases with LCBCC system at WS1 was more close to neutral level than cases with CCMV system ($p<0.05$). In fact, the positive impact of the higher convective cooling at WS1 can be seen during the exposure in conditions with LCBCC. The first vote at WS1-2 under LCBCC shows OTS reduced and approached the neutral level in the studied conditions. Conversely, because of the effect of the simulated window and floor, OTS at WS1-2 was assessed close to slightly warm under CCMV.

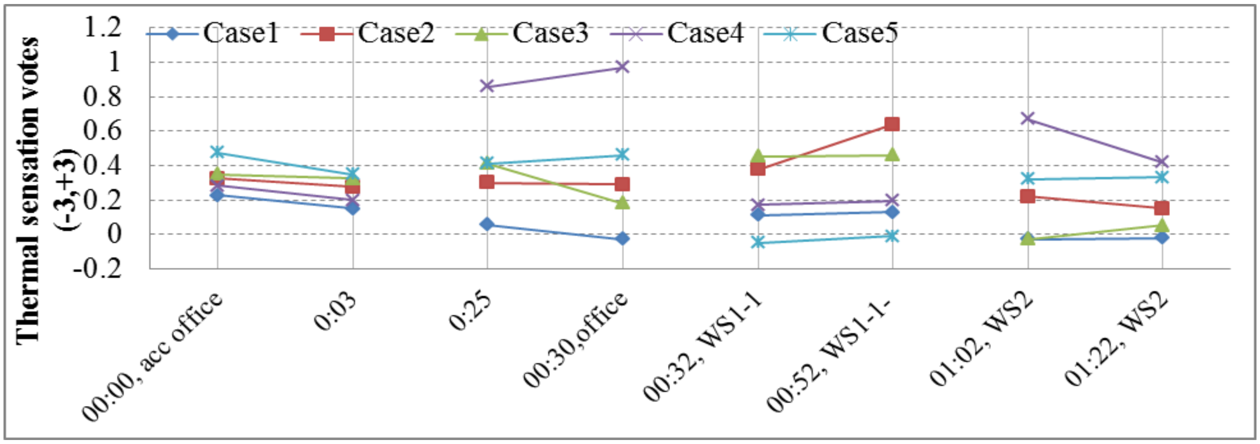

Figure 3. The median value for overall thermal body sensation with all studied systems. The scale is: -3 – "Cold", -2 – "Cool", -1 -"Slightly cool", 0 - "Neutral", 1 - "Slightly warm", 2 - "Warm", 3 –"Hot"

As shown in Figure 4, the LTS votes in cases with LCBCC, i.e. cases 1, 2 and 3, were close to neutral at WS1 and subjects experienced warmer condition at WS2. The reverse pattern is seen for cases with CCMV system. Due to the effect of downward flow at WS2 and the absence of warm floor and simulated window LTS votes were close to neutral level at WS2 while WS1 was assessed warmer by the subjects. While the TS of the body parts, especially the uncovered parts such as face, hands and arms, remained almost unchanged at WS1 by changing the room's thermal condition, the TS of the studied body parts approached to the "slightly warm" limit at WS2.

In the previous study by Uth et al. (Uth et al., 2014) it was pointed out that when the LCB was used without using CC panels, the subjects were not satisfied with the thermal condition outside of the generated local-environment. Considering the last votes at WS1, before and after moving to WS2, shows a slight reduction in OTS values under all tested conditions. This can be attributed to the influence of CC on the whole body thermal sensation of the occupants. The results of subjects' satisfaction of thermal environment reveal that this disadvantage did not exist when the LCB was combined with the CC panels.

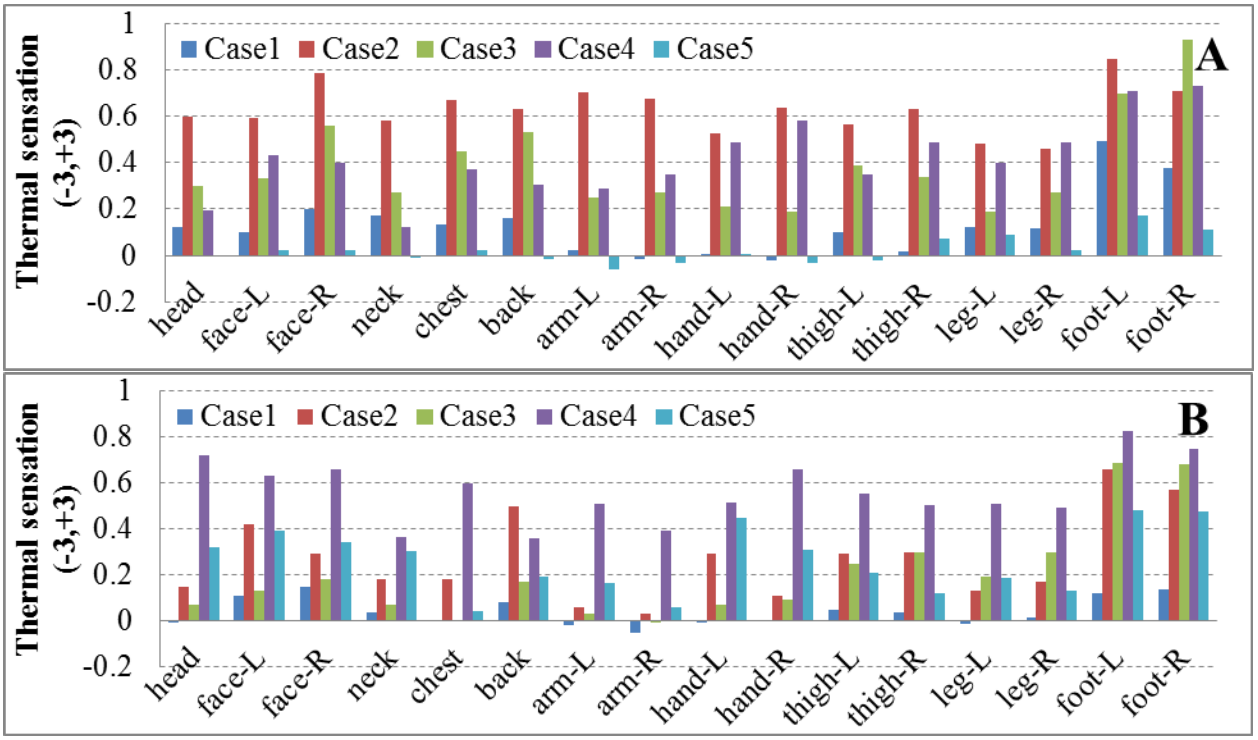

Figure 4. LTS votes of body parts at A)WS2, and B) WS1-2. The scale is: -3 – “Cold”, -2 – “Cool”, -1 - “Slightly cool”, 0 - “Neutral”, 1 - “Slightly warm”, 2 - “Warm”, 3 –“Hot”

Airflow control and air movement

More subjects perceived AM in cases with LCBCC system, Figure 6. The perception of AM increases with decreasing air temperature and it was considerably higher in upper body parts, especially in uncovered ones. Although no substantial difference was observed between number of votes with LCBCC under tested thermal conditions, the positive effect of convective cooling in improving AM acceptability was more pronounced in the higher room temperature (Figure 5). Comparing the results for the left and right side of the body in Figure 5 shows that fewer subjects perceived AM at WS1 on left side of the body than the right side. This could be interpretted as the effect of radiation from the local heat source , i.e. simulated window, on the left side of the body.

Considering the low values of standard deviation, airflow remained almost unchanged during the experiment in many cases. This can be concluded as either changing the airflow was not prioritized by some of the subjects, or they felt comfortable so that they didn’t want to change the local -climate thermal condition. By taking the votes of LTS, AM acceptability and number of subjects perceived AM, the latter possibility is more likely. Rather similar votes of LTS and AM acceptability imply that subjects were generally satisfied with the local -environment generated by the LCBCC at WS1, regardless of the differences in the adjusted airflow rate.

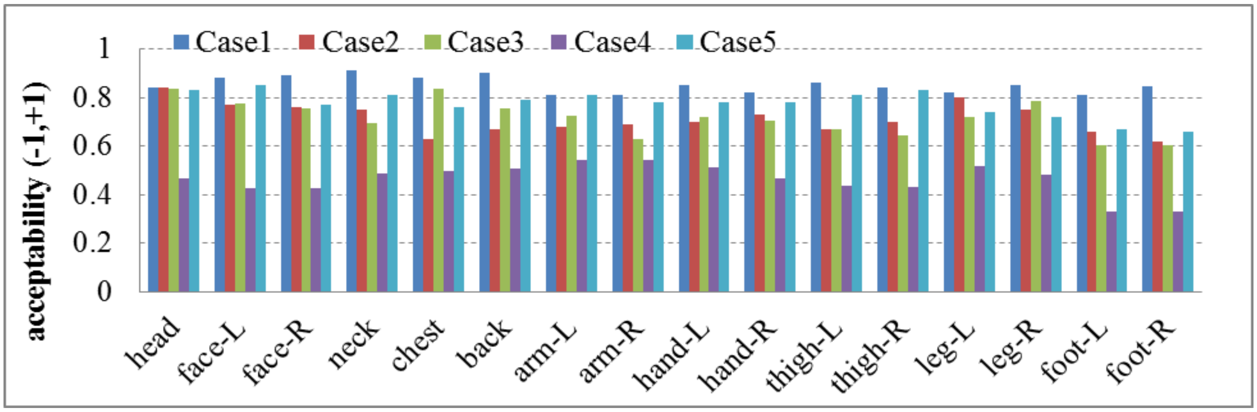

Figure 5. AM acceptability at different body parts in five systems at WS1-2

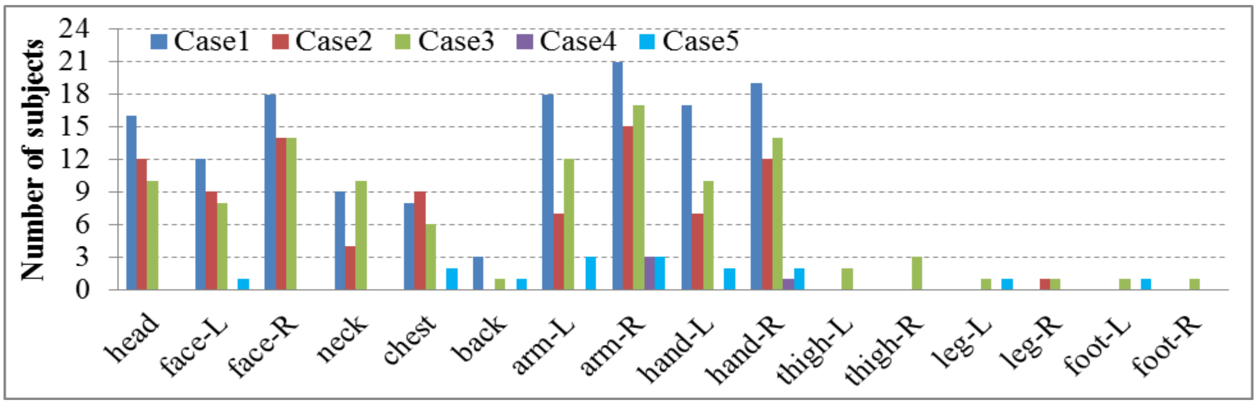

Figure 6. Number of subjects perceived AM on one or more body parts at WS1-2 with tested systems

Because the subjects were provided with control of the supplied airflow most of them preferred no change in the airflow rate and only few people wished for more or less supply airflow rate. The OTS votes of subjects who wanted "no change" in airflow rate was within the neutral range, i.e. between -0.5 and +0.5, and the adjusted airflow rate by these subjects was in the top half of the airflow range, i.e. between 11.5 L/s and 13.0 L/s. The subjects who reported LTS less than neutral and wanted less air on the same body part were considered bothered by draught. Altogether, four subjects (17%) in case 1, two subjects (8%) in case 3 and two subjects (8%) in case 5 felt slightly cool and wanted less AM in particular body parts. Apparently, the most problematic regions evaluated by the participants in terms of local thermal discomfort and AM were hands and arms. In case 1, one subject wished for less airflow rate while didn't intend to decrease the airflow rate. In addition, one subject (4%) in cases 1 and 3 and two subjects (8%) in case 2 at the end of the first exposure (WS1-2) adjusted airflow rate at the maximum and still reported warm OTS. These findings could be a result of the insufficient cooling provided by the LCBCC system.

Conclusions

The results of thermal sensation (OTS and LTS) reported by the subjects at the workstation showed that the LCBCC created a thermal sensation close to the neutral level for the occupants. The combination of CC panels with LCB also generated acceptable thermal environment also in the rest of the occupied zone.

Most of the subjects were satisfied with the air movement at WS1 in the cases with LCBCC, while they reported request for more air movement in the case of CCMV.

Overall and local thermal sensation votes indicate that the cooling performance of the LCBCC when operated at minimum airflow rate (10 L/s) was almost the same as CCMV with 13 L/s. This can be regarded as a major benefit of the LCBCC system over the CCMV system from the energy saving point of view.

Acknowledgements

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